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POLISH ACADEMY OF SCIENCES

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113

Selected papers from the International Conference on *Turbines of Large Output* devoted to 100th Anniversary of Prof. Robert Szewalski Birthday, Gdańsk, September 22-24, 2003

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GDAŃSK 2003

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Aims and Scope
Transactions of the Institute of Fluid-Flow Machinery have primarily been established to publish papers from four disciplines represented at the Institute of Fluid-Flow Machinery of Polish Academy of Sciences, such as:

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- Gas and liquid flows with heat transport, particularly two-phase flows,
- Various aspects of development of plasma and laser engineering,
- Solid mechanics, machine mechanics including exploitation problems.

The periodical, where originally were published papers describing the research conducted at the Institute, has now appeared to be the place for publication of works by authors both from Poland and abroad. A traditional scope of topics has been preserved.
Only original and written in English works are published, which represent both theoretical and applied sciences. All papers are reviewed by two independent referees.

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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 113, 2003, 3-4

Editorial

These Special Issues of the *Transactions of Fluid-Flow Machinery*, Nos. 113 and 114 contain selected papers from the International Conference on *Turbines of Large Output* devoted to commemorate 100$^{\text{th}}$ Birthday Anniversary of Prof. Robert Szewalski. The conference was held in Gdańsk, Poland on September 22-24, 2003.

The Conference is a continuation of previous conferences held at the Institute of Fluid-Flow Machinery PAS in former years dedicated to technology of steam turbines. Series of conferences bearing the same name took place in the years 1962, 1965, 1968, 1993. In 1997 organised has been a conference on steam turbines and related topics, but with a slightly amended title – *Problems of Fluid-Flow Machinery.* At present at the Institute of Fluid Flow Machinery there are conduced research of fundamental character encompassing both the issues related to steam turbines and fundamentals of power engineering.

Organisers of the present conference have returned to the traditional name, i.e. Conference on *Turbines of Large Output* to mark the respect to the memory of Professor Robert Szewalski (1903-1993), the founder and a director of the Institute of Fluid-Flow Machinery for several years, and initiator of the conference series devoted to the problems of steam turbines.

The Editors are very grateful to the referees of the papers presented in this issue of the *Transactions of Fluid-Flow Machinery*: J. Badur, W. Batko, E. S. Burka, J.T. Cieśliński, P. Doerffer, A. Gardzilewicz, B. Grochal, J. Kiciński, G. Kosman, T. Król, J. Krzyżanowski, J. Mikielewicz, A. Neyman, W. Ostachowicz, R. Puzyrewski, R Rządkowski, J. Świrydczuk, M. Trela, T. Uhl and Z. Walczyk.

We appreciate cordially the manifested authors interest in our conference. Special thanks are conveyed to Ms 'Maya' Bagińska, for her fruitful editorial help related to directing the papers to reviewers and correspondence with the authors of contributions.

Prof. Jarosław Mikielewicz
Editor-in-Chief

Dr Edward Śliwicki
Managing Editor

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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Measurement of dispersivity and moisture content in experimental turbines by optical methods

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Abstract

The issue of using optical methods for measurements of moisture drops sizing and their concentration in a zone of steam flow condensation are set forth in this paper. A practical applications of optical indicatrice, spectral transparency, and "narrow angles" methods are shown. Main principles of probe construction to investigate two-phase medium are outlined. Practical results of investigations performed on experimental stands and a full-scale turbine are given.

Keywords: Steam turbine; Wetness measurement; Optical methods

Nomenclature

C	–	concentration of the moisture volume,
I_0	–	initial radiation intensity,
$i(r,\beta)$	–	angular distribution of radiation scattered by a single particle,
$K(\rho)$	–	attenuation coefficient of radiation scattered by a single particle,
L	–	ray path length in medium (translucence dimension), m
$N(r)$	–	law of droplets distribution according to sizes,
r	–	droplet radius, m
m	–	constant depending on the refraction index of the droplet,
λ	–	wavelength of light, m
$\rho = 2\pi r/\lambda$	–	diffraction parameter,
v_s	–	specific volume of steam at measured point, m^3/kg
v_w	–	specific volume of water at measured point, m^3/kg

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1 Introduction

A critical problem of study of moist-steam flows, streaming in a turbine setting, is to research their fractional composition. Optical structure defining methods of moist-steam flow are the most acceptable among other methods [1]. To size fine (process) moisture an indicatrice and spectral transparency methods are used [2, 3]. "Narrow angles" methods are applicable in poor-dispersion (secondary) moisture measurement [4]. Below is a description of these methods and hardware decision regarding sizes and concentration measurement of droplets.

Main characteristics of light-diffusion effect, on which measurement a dispersible analysis is based, are an indicatrice (polar chart) of radiation diffused with droplets

$$i(\beta) = \int i(r,\beta)N(r)dr \tag{1}$$

and radiation attenuation

$$i(\lambda) = I_0 \exp\left[-\int K(\rho)N(r)\pi r^2 L dr\right]. \tag{2}$$

1.1 Indicatrice method

Indicatrice method (MI) is based on the following principle: in some area of droplets, with certain sizes intensities, ratio of light scattered by droplet under different angles is a monotonic function of its size. Calculation of dispersion indicatrice by known formulas of the above-mentioned method allows defining such dependence. Calibration curve of the light intensity ratio dependence under 8° and 20° angles from water droplets radius is shown in Fig. 1.

Construction of the probe head and the measurement system are given in Fig. 2. Besides the measurement of droplet radius, this system allows determination of the steam flow humidity. By metering the light attenuation at a translucent base and knowing a priori measured droplet radius, the method enables determination of volume concentration of droplets – C would be calculated. Humidity degree – Y is related to volume concentration by the ratio:

$$Y = \frac{C}{C + \frac{v_\omega}{v_s}}. \tag{3}$$

Such probe, implemented at MPEI experimental turbine, a enables estimation of the influence of different concentrations of micro admixtures on moisture droplets dimension in the steam condensation zone. Moisture droplet measurement results at different initial concentration of sulphates in steam in front of the turbine are presented in the diagram in Fig. 3.

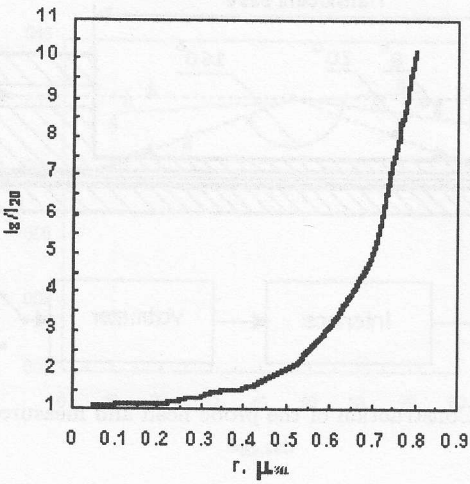

Figure 1. Calibration curve for ratio $I_{8°}/I_{20°}$.

1.2 Spectral transparency method

Spectral transparency method is applicable to measure dimensions of droplets, which do not exceed several microns. In the present paper a method based on the following principle is outlined: combination of medium transparency measurement for two wavelengths and application of the preliminary information concerning the law of droplets distribution by dimensions.

The spectral content of the radiation attenuation is determined, according to (2), from the character of dependence $K(\rho)$, which is known from the MI theory as a radiation attenuation factor by the solitary droplet. Examining this relation for the water droplets, (Fig. 4), the typical areas (however, they don't have clearly marked bounds) differentiated by the diffraction parameter ρ, can be marked out on it which characterize the relationship between the water droplet size and the wavelength of the scattered light:

- area of exponential dependence ($\rho \ll 1$),
- area of extreme dependence ($1 < \rho < 10$),
- area where the attenuation factor asymptotically tends to the constant value of $K(\rho) = 2$ ($\rho > 10$).

Application of the method in these three ranges allows obtaining the different information about the dispersion structure of the moisture-steam flow.

When $\rho \ll 1$ (the area of very small droplets) the so-called Rayleigh scattering

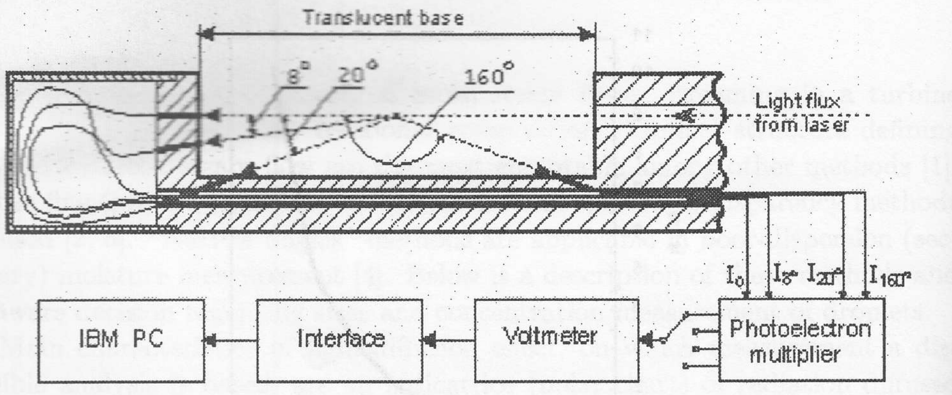

Figure 2. Construction of the probe head and measurement chart.

takes place, under which the radiation attenuation is inversely proportional to the 4^{th} power of the wavelength. According to (2):

$$\ln \frac{I_O}{I_(\lambda)} = \frac{\alpha L C r^3}{\lambda^4}. \tag{4}$$

In the area of the droplet size commensurable with the wavelength $1 < \rho < 10$. According to (2), the relative attenuation of the light flow is

$$\ln \frac{I_O}{I(\lambda)} = \pi L \int K(\rho) r^2 N(r) dr. \tag{5}$$

Consider

$$\bar{K}(\rho) = \frac{\int K(\rho) r^2 N(r) dr}{\int r^2 N(r) dr}. \tag{6}$$

Substituting the last relation into (5), we have:

$$\ln \frac{I_O}{I(\lambda)} = \pi L \bar{K}(\rho) \int r^2 N(r) dr \tag{7}$$

Now we enter the Sauter droplet size as the relation for the third moment of the droplet distribution by their sizes to the second moment

$$r_{32} = \frac{\int r^3 N(r) dr}{\int r^2 N(r) dr}. \tag{8}$$

Evidently, the denominator of this relation is proportional to the volume concentration of the droplets

$$C = \frac{4}{3}\pi \int r^3 N(r) dr. \tag{9}$$

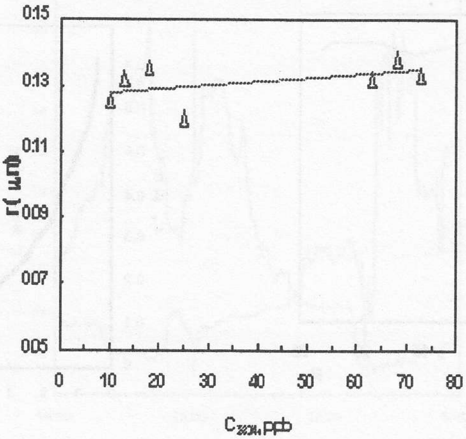

Figure 3. Change of droplet radius subject to concentration of sulphates in the steam in front of the turbine (Y =const= 0.7%).

Therefore, the light relative attenuation

$$\ln\frac{I_O}{I(\lambda)} = \frac{0.75L\bar{K}(\rho)C}{r_{32}} \tag{10}$$

is determined by the size and the volume concentration of the droplets.

The relation between two logarithms of light attenuation of two wavelengths can be designated as:

$$F(r_{32}) = \frac{\ln\frac{I_O(\lambda_1)}{(\lambda_1)}}{\ln\frac{I_O(\lambda_2)}{(\lambda_2)}} = \frac{\bar{K}(\rho_1)}{\bar{K}(\rho_2)} \tag{11}$$

As calculations, made by the Mie theory formulas, show that this relation is the monotonic function of the Sauter droplet size in the range r from 0.06 μm to 0.7 μm (Fig. 5).

Therefore, on the basis of this relation, we can determine the mean droplet size. When the droplet size is known, from the Eq. 10 the volume concentration can be found

$$C = \frac{r_{32}\ln\frac{I_O}{I(\lambda)}}{0.75L\bar{K}(\rho)}. \tag{12}$$

When the volume concentration is known, the degree of the flow humidity can be determined (see Eq. 3). That is, for the measurement of the typical size r_{32} and the degree of humidity, it is necessary to have the information about the form of

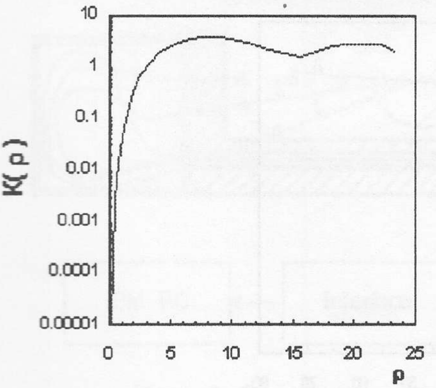

Figure 4. Radiation attenuation factor for water droplets.

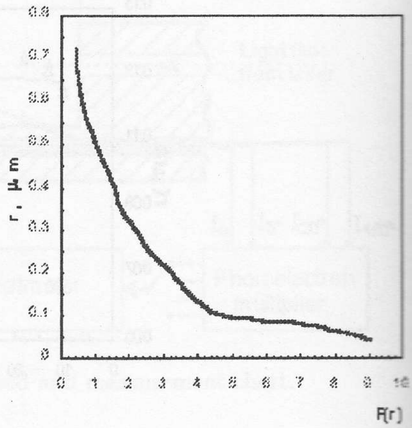

Figure 5. Function F, rated value.

the distribution droplets law by their size $N(r)$.

In the range of big droplets ($\rho > 10$) the attenuation coefficient does not depend on the wavelength. Thus, the measurement of the transparency

$$\ln \frac{I_O}{I(\lambda)} = \frac{1.5LC}{r_{32}} \tag{13}$$

allows measuring the second distribution moment (average surface of the droplets). Basic scheme of measurement setup is presented in Fig. 6. Spectral transparence

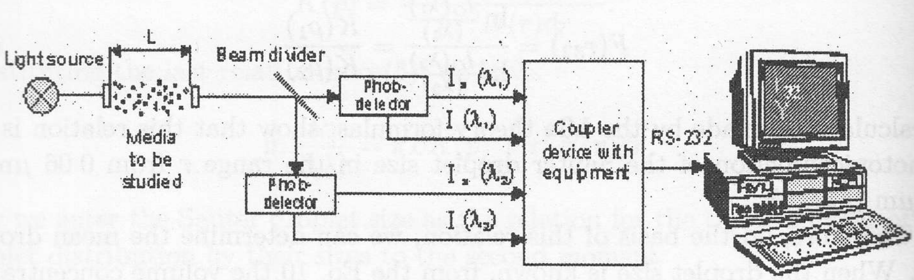

Figure 6. Basic scheme of measurement complex.

method is laid in the principle of the probe, which is helped to measure a droplet size and humidity at a full-scale turbine of 50MW capacity. As an example, droplets radius and humidity change in time are given in Fig. 7.

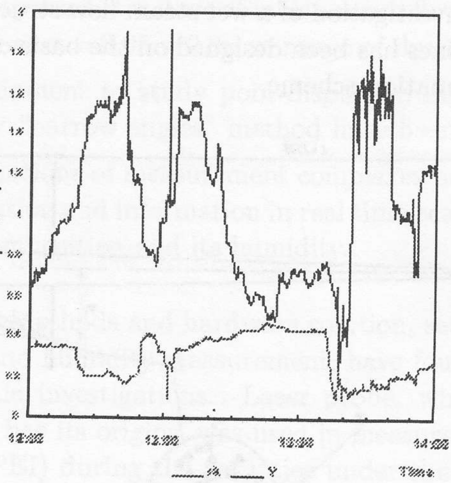

Figure 7. Change in droplets radius and humidity on a full-scale turbine of 50 MW capacity.

1.3 The small scattering angle probe

The small scattering angle method (SSAM) is based on the recording of the light scattering indicatrice (1) in a small spherical angle β forward, within the range of the first diffraction ring, from the droplet, which is significantly larger than the scattered radiation wavelength ($\rho > 10$). For this particular case, an accurate solution of the light scattering integral equation, yielding the reconstruction of the size distribution of the droplets, is known exactly as:

$$N(r) = B \int_0^\infty J_1(\rho, \beta) Y(\rho, \beta) \frac{d}{d\beta} \left[\beta^3 I(\beta)\right] d\beta, \qquad (14)$$

where $J_1(\rho, \beta)$ and $Y(\rho, \beta)$ are, respectively, the Bessel functions of the first and second kind.

The SSAM is mostly utilized to determine the size spectrum of the droplets. However, the absolute measurements of the indicatrice with the parameters, forming the B constant, taken into account, yields calculating of the absolute values of $N(r)$, that, in turn, gives an opportunity to calculate the volume concentration of the droplets. The working range of the method is limited from below at a level of $r = 3..5$ microns by the divergence of the incident radiation and technical difficulties of the indicatrice registering in a small spherical angle.

$$Q_3 = a \int_0^\infty I(\beta) d(\beta), \qquad (15)$$

A probe for the investigation of a wet steam flow structure in the low pressure cylinders of real turbines has been designed on the basis of the SSAM. The probe is using the autocollimation scheme.

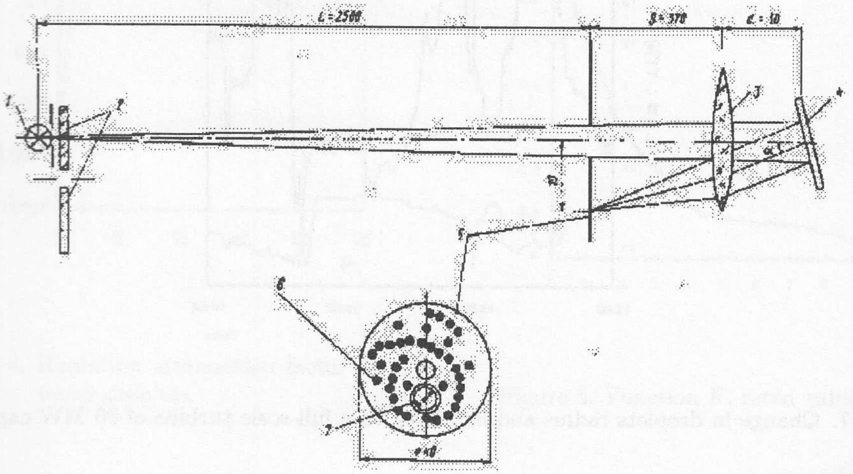

Figure 8. A scheme of the small scattering angle probe.

For the light source 1 a high-pressure mercury lamp is used, and to register the light spot a mosaic 5 of miniature photo resistors 6, 7 is utilized. The measured volume is situated between the objective 3 and reflector 4. The dimensions of the probe (length 3 m, rod diameter 60 mm) make it possible to use it for measurements inside the interstage clearances of the last stages of the turbines. The probe is equipped with a monitoring system of its vibrations.

The described probe has been utilized for the measurements in the area after the last stage of a real turbine of 300 MW capacity. The secondary moisture mass size distribution spectra, corresponding to different areas of the steam flow (from the root to the peripheral blade cross-sections) was obtained at the nominal and intermediate modes of the turbine operation. In al the cases the measurements produced a close to normal distribution with the dispersion $\sigma^2 = 0.44$ and the average radius of 3...7 microns, and indicated a sharp growth of the droplet size towards the blade edges.

2 Conclusions

The above-stated data allow drawing the following conclusions:

- based on MI and spectral transparence method the measurement systems, to investigate a dispersed structure of moist-steam flow in experimental and full-scale turbines at $r = 0.05 - 0.8\mu$ m range of droplets size, are created,

- methods and equipment to study poor-dispersion moisture in a full-scale turbine setting by "narrow angles" method have been developed,
- conducted examinations of measurement complexes have shown acceptable reliability of operation and information in real time-scale in respect to steam flow dispersion composition and its humidity.

Acknowledgements Methods and hardware solution, set forth, regarding the problem of dispersion and humidity measurement, have found application in experimental and full-scale investigations. Laser probe, where principles of MI (method of indicatrice) has its origins, was used in measurements at experimental turbine ET-3M (MPEI) during the activities under the contract with EPRI [4]. Optical probe, based on the spectral transparence method, was proven at a full-scale turbine of 50 MW of Eskhar Power Plant, Ukraine. Work on particle charge determination was done in co-operation with the Institute of Machine Building problems of Academy of Sciences of Ukraine [5]. Optical probe has also been used during investigations on MPEI (ET-12) experimental stands.

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